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N.M. STANDEN, S.E. ROSBOROUGH

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N.M. Standen, Chief, Aeronautical Technology Development, and
S.E. Rosborough, Analyst, Civil Aeronautics Directorate,
Transport Canada, Ottawa, Ontario, Canada

ABSTRACT

A computer program has been developed to assess the fuel consumption of jet transport aircraft in terminal area operations. Performance characteristics of the Boeing 737 type aircraft have been used to determine the fuel consumed and the noise levels produced under several departure profiles normally considered as noise abatement procedures. An index is suggested which is intended to provide a measure of the relative effects of fuel consumed and noise level experienced by groundbased observers.

INTRODUCTION

Increases in the price of aviation fuel over the past several years are generating fundamental and permanent alterations in the functioning of the aviation industry. Aircraft and aeroengine manufacturers, aircraft owners, airlines and regulatory agencies are all tailoring their product, whether it be hardware, transportation service or management of the air navigation system, to the hard reality of limited availability of expensive fuel.

While manufacturers and aircraft operators can be seen to be working strenuously to counter the effects of fuel scarcity and fuel cost, regulatory agencies may not always appear to recognize the severity or the immediacy of these effects. This appearance may be exaggerated because the products of a regulatory agency are certification standards and regulations, which might seem to be easier to change to save fuel than the gas path of a turbine engine, the aerodynamics of a wing or the route structure of an airline. Indeed, since the regulatory agencies must ultimately approve the machines or operations that result from a change in gas path, wing design or airline route structure, their attitude towards fuel conservation is important to the successful application of a designer's, or operator's, attack on the fuel consumption problem.

This image of regulatory agencies is probably nowhere stronger than in areas of environmental protection. The quantification of benefits derived from measures taken to reduce the environmental impact of aviation lagged behind the axiomatic realization that the impact had to be reduced. Indeed, the aviation industry committed significant resources to reducing environmental impact, principally in the form of noise, on the basis of social indicators such as community annoyance. The costs of these efforts are not readily attributable to environmental protection, however, since they may appear as modifications to capital and maintenance costs, or they can be charged against other benefits, such as fuel economy. Some work has been done to evaluate the economic benefit of the resulting environmental impact relief, but such conclusions as could be drawn from this work have not constituted the impetus for impact reduction in the classical sense of benefit to cost comparisons of alternatives. Very simply, the impetus for reducing aircraft environmental impact, specifically noise, was the fact that aircraft were demonstrably noisy, and communities near airports perceived this noise to be excessive.

The rapid escalation in aviation fuel cost, and the limited availability of fuel on occasion, have changed this situation and complicated it. When fuel was cheap and plentiful, the extra consumption of fuel to achieve noise abatement was a small addition to total cost. Now, however, it is a significant cost, and one borne directly by the aircraft operator. Apart from the cost of resources committed to achieving the low-noise technology,the problem is how much extra fuel is consumed to provide how much noise relief.

This paper addresses that question. No attempt is made to address the economic assessment of costs involved -- the true cost of aviation fuel or the complete benefits of low noise impact. Rather, this paper reports a model used to define the fuel consumed and the noise level produced at individual locations on the ground, corresponding to residential communities under the flight path. It goes one step further, but not beyond past practice, in translating the ground noise level into a measure of community acceptability. We leave the determination and assignmemt of economic values to the economists, fully appreciating that their task is by no means straight-forward, particularly with respect to noise impact. An approach which measures the cost of interference and interruption due to noise in a business environment could be postulated, perhaps based on salary levels, but a parallel approach in a residential setting is less apparent. The costs of people's time and inconvenience in a residential or recreational situation are difficult to define, to judge from the literature. Nonetheless, since work has been done on the economic effects of noise on residential properties in the aggregate[1,2], there may be some workable approach to defining the components of that aggregate cost.

METHOD

Detailed engineering data, describing the performance and noise characteristics of transport aircraft, were used to construct a computer program. The Performance Engineering Manual[3] of the Boeing 737-200 powered by Pratt and Whitney JT8D-9A engines provided the specific aerodynamic and performance data for this study. These data were programmed using both tabular and curve-fitting methods to produce the necessary data sets. The computer program uses this data and a departure profile schedule to compute the aircraft condition at various points on the flight path, applying equations of motion and aerodynamic relationships. The condition of the aircraft is described by its altitude, weight, distance from brake release and speed. This information is provided to the user, along with the derived information of fuel flow rate, fuel consumed and noise level on the ground below the flight path. Pertinent aerodynamic and engine data such as lift and drag coefficients and engine pressure ratio, are also made available.

The departure profile schedule is, of course, the independent variable of the analysis. In specifying a departureprofile, several events and procedures are sequenced to describe the desired changes in aircraft condition and configuration along the flight path. These include flap retraction, the reduction from take-off thrust to a specified climb thrust, any further reduction to some minimum level of thrust for noise abatement, increases in speed and the resumption of higher thrust levels. The computer program has the ability to simulate a departure profile schedule composed of these procedures in almost any order, as well as the flexibility to allow control by the user over the climb rate, the climb gradient with one engine inoperative, the maximum climb speed, the amount of noise abatement thrust reduction, and the number and positions of noise monitoring points.

The flight path is divided into several sections, and the required data is calculated for each sequentially. Typical sections are:

1. From brake release to 35 ft. altitude;
2. From 35 ft. altitude at take-off thrust to the reduced thrust transition point or to the flap retraction initialization point, whichever is lower;
3. From the thrust transition point to the flap retraction initialization point or vice versa, depending on the previous section;
4. During the flap retraction, one section for each reduction of flap setting from the initial flap setting to zero;
5. From the end of the flap retraction to 10,000 ft. altitude, in steps of 1,000 ft. (each step is a section).

The flight paths considered in this paper are two-dimensional, in that they allow only a variation of height with distance from brake release. Many noise abatement departures specify a ground track to be followed as well, which means that the flight path is three-dimensional and not simply flown along the extended runway centerline. While such a vectoring procedure undoubtedly consumes additional fuel for the sake of noise relief, it is a procedure specific to a particular airport and community arrangement. It is therefore impossible to generalize such a procedure, as the departure schedule can be generalized, so the additional fuel consumption due to vectored departures is not considered in this paper. The calculation method is fully capable of incorporating such a three-dimensional flight path, however, with the inclusion of simple geometric relationships and aircraft turning manoeuvres in the departure schedule.

Having specified a particular departure schedule, the calculation results of immediate interest are the fuel consumed and noise level on the ground below the aircraft. These data are provided at the end point of each flight path segment. The fuel consumed is summed in a running total to provide the total fuel consumption for the take-off, from brake release to 10,000 feet altitude. While the fuel burned on each segment is an important item to consider in constructing effective departure schedules, and would be useful in devising three-dimensional noise abatement profiles, the total fuel consumption for the take-off is the fuel parameter of interest here. Once the aircraft has been committed to a particular departure schedule, it has also been committed to burn a particular quantity of fuel. Whatever criterion is chosen to evaluate the degree of noise relief provided by the departure schedule, the fuel cost comparison must be based on the total consumption for the entire take-off.

The noise impact parameter is a different matter, however. The noise level of the take-off can be expressed in terms of instantaneous, usually maximum noise levels (measured by Perceived Noise Level, PNL, or by a simpler weighting, such as dBA), or in terms of an overall noise dosage (measured by Effective Perceived Noise Level, EPNL, Single Event Noise Level, SEL, etc.). In either case, the impact depends upon the location of the receiver relative to the flight path. Indeed, the objective of a noise abatement procedure is to provide relief from noise at specific noise-sensitive locations on the ground, most likely residential communities along the flight path. It is therefore appropriate to compare aircraft noise levels at intermediate segments of the departure schedule, corresponding to points on the flight path above specific ground sites. The comparison of departure schedules in this paper is therefore in the form of ground noise level at each point below the flight path, and total fuel consumption for that flight path.

Finally, it should be noted that the noise levels quoted are for points directly under the flight path, and do not describe noise levels propagated over longer distances lateral to the flight path, nor include ground attenuation effects. Again, such additional considerations would be required in evaluating three-dimensional flight paths, but the calculation procedure would then require modification for geometric relationships and acoustic propagation phenomena.

DESCRIPTORS

As explained previously, the purpose of this study is to produce a comparison of the noise impact and fuel consumption that will provide the starting point for a socio-economic analysis of the noise abatement procedure. Thus the descriptors of fuel consumed and noise impact, as used in the output of this method, must be in a form appropriate for socio-economomic assessment.

In this sense, we have presumed that the quantity of fuel consumed, in weight or volume measure, is an appropriate index. Simple economic evaluations of the fuel parameter, such as cost or replacement value, are readily applied to the quantity of fuel consumed. We would expect that more complex economic evaluations relating to energy expenditures could also effectively begin with quantity of fuel consumed.

The noise impact index is somewhat different. The level of noise in itself is not an appropriate parameter because it is the impact of noise on people that is damaging, not the noise itself. This may seem like a fine, perhaps unecessary distinction, but it is precisely this relationship that has been the objective of much of the re-search over the past two decades into the effects of noise on man. Studies and reports such as References 1,2,4 and 5 demonstrate how measures of noise level are translated into symptoms of human impact (individual and community impact) then into assessments of health, welfare and economic costs.

It has been widely observed that almost all recognizable effects of a given noise on individuals will vary greatly in severity, depending upon the individual and the circumstances. Certain general statements can be made concerning reactions of individuals, but to apply to a large enough sample of humans, such statements almost always are too general for practical use. The major effort in assessing the impact of community noise (as opposed to noise in the work place), has therefore concentrated on community reaction to noise, thereby averaging the reactions of individuals over a large number of people. Several community reactions to noise have been postulated as indicative of the impact on the community, but the one effect most often used is the fraction of the population highly annoyed because of the noise, as determined by community surveys. Over the years a certain concensus has been established quantifying the term "highly annoyed", justifying the use of this measure(6).

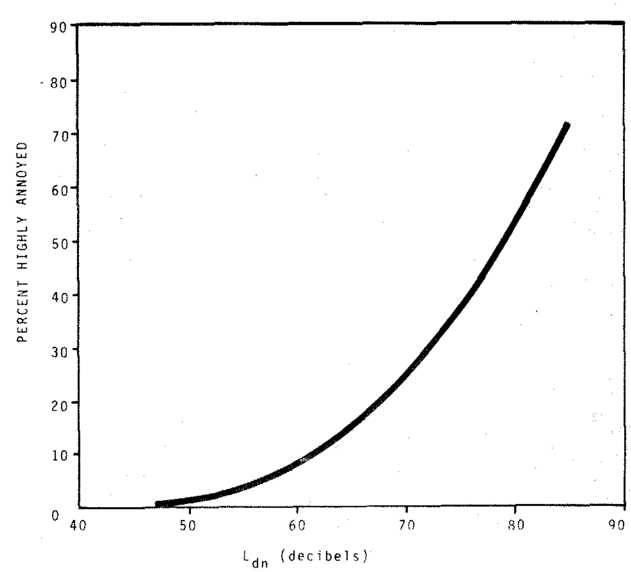

Fig. 1. Population Reaction to Community Noise, Based on Social Surveys, from Ref. 6.

The noise index invariably used in establishing the relationship between community impact and noise level has been the total noise "energy" or dosage. This noise dosage is effectively the integral over time of the subject noise level. To date, several indices describing the noise dosage have been proposed and are in general use. Among them, the most common are the Equivalent Sound Level (Leq), the day-night equivalent sound level (Ldn), the aircraft Noise Exposure Forecast (NEF), and others similar to the latter which are specific to aircraft. The mathematical definitions of these noise dosage indices are given in several standard references, including Reference 4.

Schultz [6] clearly shows that the carefully designed surveys done in the past lead to the conclusion that the impact of noise on a community varies non-linearly with noise dosage (Figure 1). Whatever measure of the impact that is used, the degree of adversity of noise on a population increases at a faster rate the higher the noise level. Other studies, such as that of Hall, Birnie and Taylor[7], report a linear relationship between impact and noise level, but Reference 7 quite clearly cautions that their results apply to a narrow noise range, and therefore probably constitute a linear fit to a segment of a non-linear curve.

Schultz [6] suggests that many of the correlations between annoyance and noise dosage level for recipients indoors could be greatly improved, lending greater accuracy to the impact-noise level relationship, if peak noise levels rather than total noise dosage were used as a measure of the noise level. References 7 and 8 provide some clues as to why this might be so. Hall, Birnie and Taylor[7] report that about 40% of the residential population near a large airport (Toronto International) experiences interruption of speech due to aircraft overflights when the aircraft 24 hour noise dosage is at Leq=55dBA, the level identified as acceptable by the EPA[4]. The percentage of population reporting such speech interference rises rapidly to more than 90% when aircraft noise dosage, over 24 hours, reaches levels where the majority of the population may be moderately annoyed by aircraft noise, and about 50% of the population is "highly annoyed". Hall et al suggest that speech interruption may be the single most significant contributor to annoyance caused by noise. They were not the first to suggest this concept. Reference 4 makes comment on it and Williams et al[8]cite early work by Borsky for the USAF which showed that speech interference is one of the principal effects of aircraft noise. Moreover, Reference 8 concluded, on the basis of the study reported therein,that speech interference played a role in individual judgements of the acceptability of aircraft noise, whether or not spoken communication was actually in progress at the time of the noise event.

Accepting a direct link between annoyance and speech interruption, Schultz's suggestion in Reference 6 would be substantiated if speech interruption were directly related to peak noise levels of aircraft flyovers. In fact, this is the conclusion which evolves from studies of speech interruption. For example, Reference 8 reports a laboratory study in which verbal comprehension was related to peak aircraft noise levels, the aircraft noise having been adjusted in both spectral distribution and level to represent the indoor perception of the peak noise signature.

In summary, we observe that a relationship between speech interference and noise acceptability has been reported in Reference 8, a relationship between speech interference and community-wide annoyance due to noise was inferred in Reference 7, and a correlation between peak noise level and annoyance due to noise was suggested in Reference 6. Combining these linkages and using the measurement results of Reference 8, we have postulated that speech interference is a reliable indicator of noise impact on individuals and by extension, on communities, that the degree of speech interference is related to peak noise levels of individual aircraft noise events, and that the relationship be-

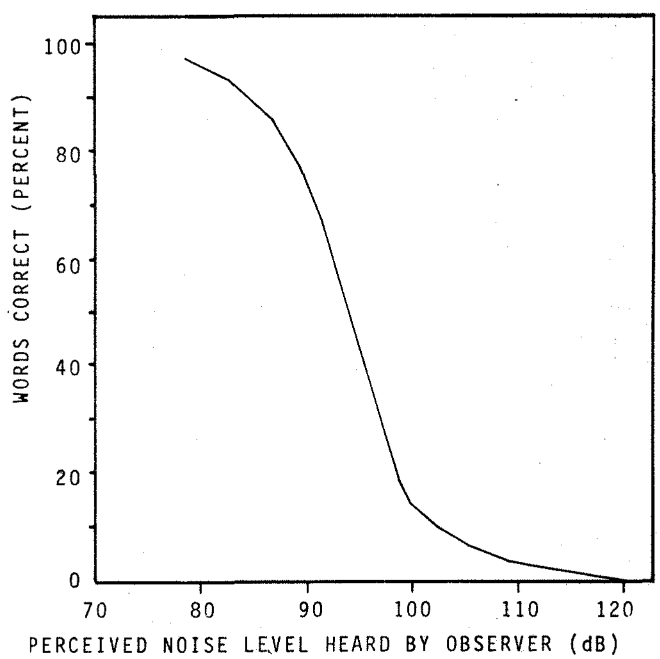

Fig. 2. Word Intelligibility in the Presence of Aircraft Noise, from Ref. 8.

tween speech intelligibility and peak noise level reported by Williams etal[8](see Figure 2) is an appropriate representation of that effect.

This connection between peak noise level and a measure of noise impact allows a rational comparison of fuel consumption and noise impact on a single flight basis. This is eminently desirable, because to construct a noise dosage index, we would have had to postulate a number of aircraft take-offs and a relative proportion of different aircraft types. Such an arbitrary assignment of numbers and mix of types would render any conclusions from this study entirely arbitrary.

We have used Figure 2 to translate our calculated noise levels for aircraft take-offs for aircraft take-offs into a noise impact, specifically, word intelligibility, and defined as the ordinate value in Figure 2 (% Words Correct) for the calculated noise level. In doing so, we have arbitrarily increased the peak noise levels of Figure 2 by 10 decibels, to approximately discount the attenuation attributed to residential structures and thereby obtain a relationship between indoor noise impact and outdoor peak noise levels. This relationship is shown in Figure 3. We have also arbitrarily extended the curve in Figure 2 to cover the noise range below 90 PNdB, by extrapolating the first three data points in Figure 2 to 100% words correct.

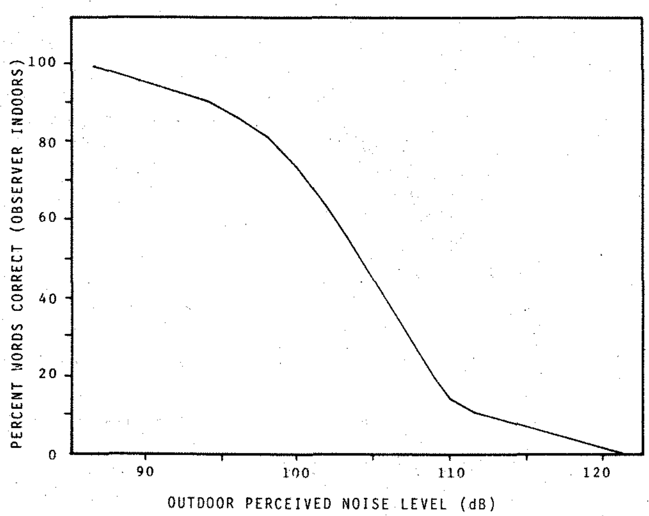

Fig. 3. Word Intelligibility in the Presence of Aircraft Noise, Observer Indoors, Noise Measured Outdoors, from Fig. 2 with 10dB Structural Attenuation.

Using the weight of fuel consumed during the entire departure schedule as the fuel parameter, and the Percent Words Correct to characterize the noise impact, we formed the ratio of these two parameters (fuel consumed/% words correct) and plotted this ratio, for all aircraft weights and departure schedules, against distance from brake release. We have adopted the term Noise-Fuel Ratio (NFR) to identify this parameter.

The concept behind this form of presentation is intended to be simple. We have expressed both fuel consumption and noise impact in terms of parameters that are or can be directly related to their economic values. The assignment of such values would therefore alter the NFR only by a multiplying factor, which would be the ratio of fuel unit cost to the monetary value of understanding verbal communication in a noisy environment. Since this ratio would be independent of aircraft type and flight procedure, it would not alter the comparisons to be made. Thus, an equal value of the NFR at a given point on the ground under two departure flight profiles implies that there is no difference between those departure profiles with respect to fuel consumption and noise impact. One profile may consume less fuel and create more noise impact at that point than the other profile, but the difference in fuel consumption is balanced by the difference in noise impact. If the value of the NFR is less than the value for another departure profile at the same ground location, the profile achieving the lower NFR value is preferred, since it yields either sufficiently lower fuel consumption or lower noise impact, or both, to provide an overall advantage.

DEMONSTRATION OF THE METHOD

It must be emphasized that the purpose of this paper (and indeed the proposed method of considering both noise impact and fuel consumption) is not to define the optimum departure schedule for an aircraft. The method does not assess any particular departure schedule on an absolute basis, even for a specified aircraft. Rather, it is a means of comparing several departure schedules, for a specified aircraft and a selected point on the ground, and thereby selecting the preferred schedule. In preparing this paper to demonstrate the method, we have not attempted to examine all available departure schedules, but have used schedules which are representative of noise abatement techniques.

Sperry [9] assessed the noise produced under five departure schedules, using three types of jet transport aircraft at various take-off weights. Reference 10 also discusses two departure schedules, but does not provide specific information concerning the aircraft used to calculate the noise impact from those schedules. For the purposes of this paper, and with comparisons of other aircraft types at some future date in mind, we used the departure schedules described in Reference 9. They are reproduced as schedules in Appendix A, with the resulting departure profiles and fuel consumptions for the aircraft in this study (B737-200) shown in Figures 4 through 7. The resultant profiles were, of course, computed using our calculation program.

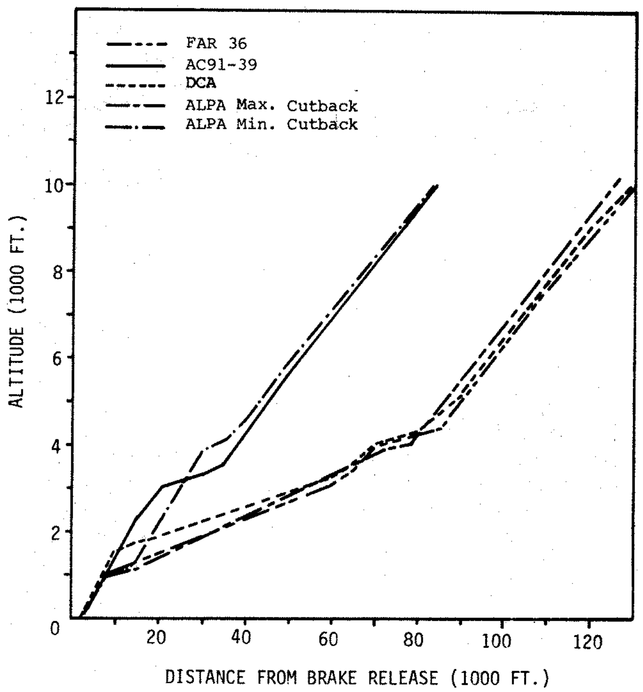

Fig. 4. Departure Prodiles, Boeing 737-200 at 80,000 Pounds Take-off Weight.

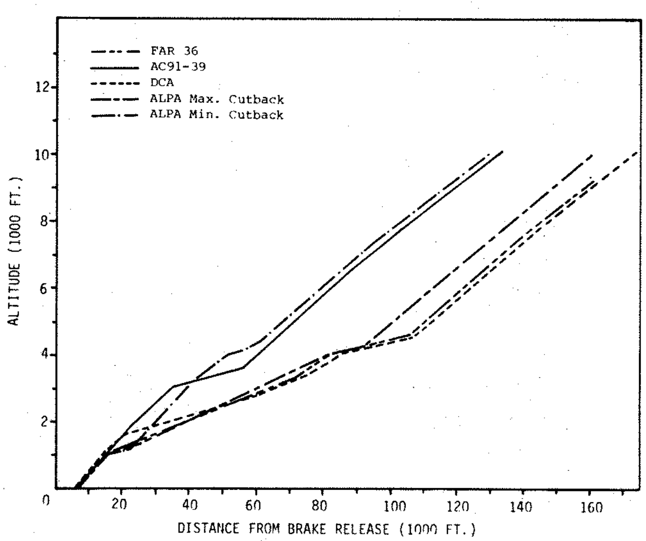

Fig. 5. Departure Prodiles, Boeing 737-200 at 110,000 Pounds Take-off Weight.

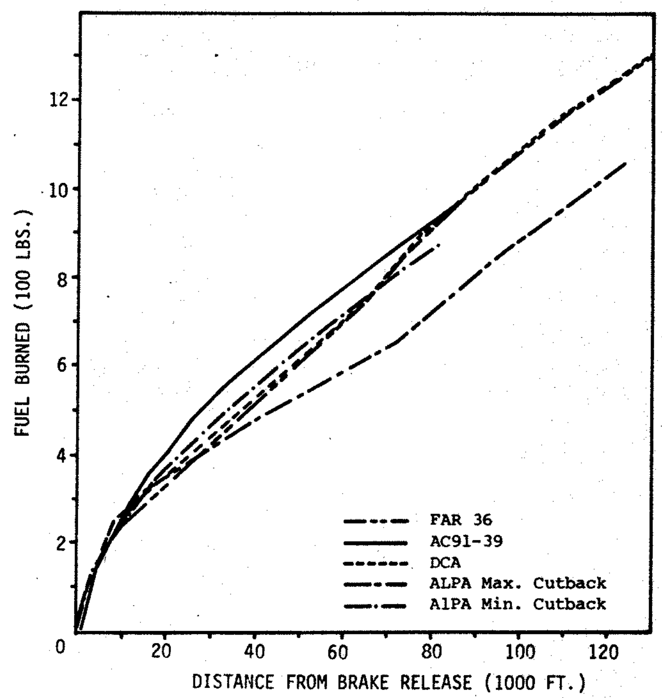

Fig. 6. Fuel Burned During Departure, Boeing 737-200 at 80,000 Pounds Take-off Weight.

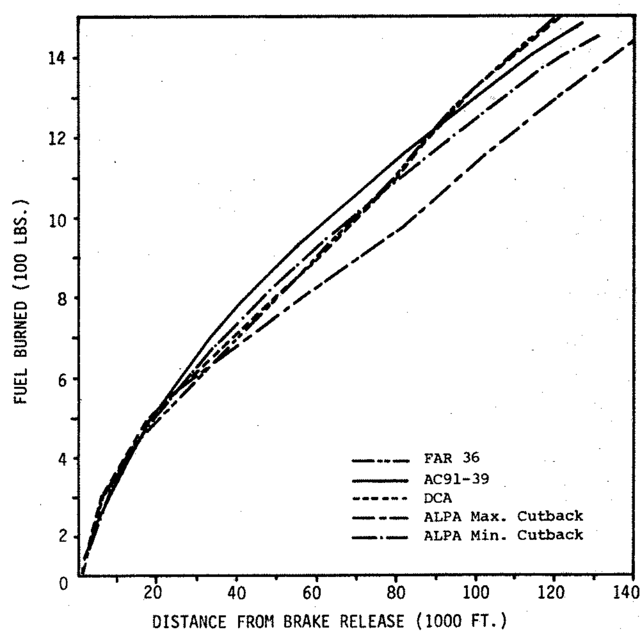

Fig. 7. Fuel Burned during Departure, Boeing 737-200 at 110,000 Pounds Take-off Weight.

Reference 9 provides some explanatory notes concerning the departure schedules, and these will be summarized here for clarity. The first schedule, denoted AC91-39, refers to a procedure recommended by the U.S. Federal Aviation Administration (FAA) in its Advisory

Circular of that number. It calls for thrust reduction to maximum climb thrust before flap retraction, and thus constitutes one version of a maximum climb departure profile. The FAA issued a new Advisory Circular, AC91-53, which was based on a revised ATA-recommended procedure. This latter circular has now superceded AC91-39. While we did not examine the effects of the schedule given in AC91-53, Sperry(9) claims that two of the profiles he examined (ALPA Max. Cutback and ALPA Min. Cutback) meet the intent of AC91-53 by performing thrust cutback after or during flap retraction. One of the schedules discussed in Reference 10, there denoted as the FAA Procedure, is AC91-53.

The ALPA schedules were recommended by the Airline Pilots Association (ALPA). The reference to Max. Cutback indicates that the thrust level for noise abatement is to be chosen to give specified positive climb gradients with one engine inoperative, or 1,000 feet per minute, whichever is greater. The reference to Min. Cutback means that a thrust level equal to the maximum climb thrust is to be used after flap retraction, thereby constituting a second version of a maximum climb departure profile.

The remaining two procedures in Reference 9 differ from the ALPA schedules in the same aspect as does AC91-39 -- the reduction in thrust is specified to occur before cleanup, rather than during or after. One of these schedules, denoted in Reference 9 as FAR 36 because it is detailed in the U.S. noise certification process, calls for acutback to a thrus equal to that necessary for one-engine-out level flight or a four percent climb, whichever is greater. It is emphasized that the FAR 36 schedule is not regarded as an operational procedure. We have in cluded it in this study to compare the effects of a large thrust cutback before and after flap retraction, the latter case being represented by ALPA Max. Cutback. The remaining schedule, denoted DCA, was developed for Washington National Airport by the FAA. It calls for a thrust cutback to a level necessary for a rate of climb of approximately 500 feet perminute, thence to maximum climb thrust at higher altitude. In Reference 10, the second procedure discussed is recommended by the International Air Transport Association (IATA), and calls for thrust cutback to normal climb thrust prior to cleanup. In this sense, it would be similiar to the DCA procedure of Reference 9.

With this background, and the flight paths resulting from the five departure schedules, we can now examine both noise impact and fuel consumption for each.

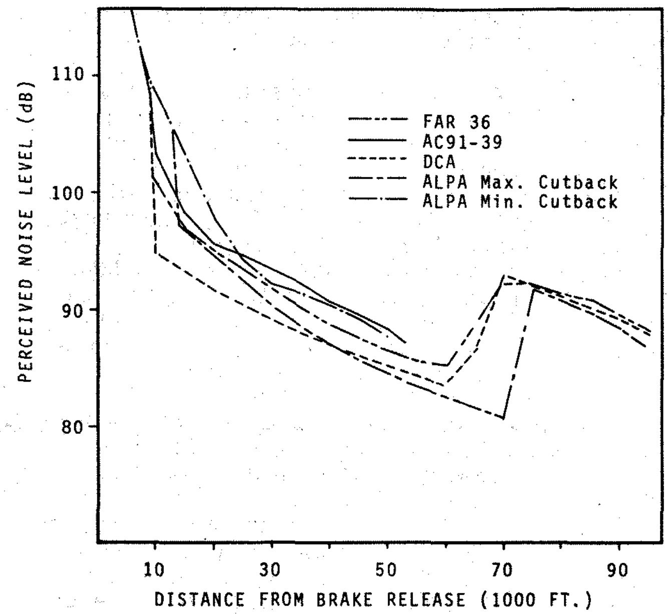

Fig. 8. Perceived Noise Levels Under Departure Path, B737-200 at 80,000 Pounds Take-off Weight.

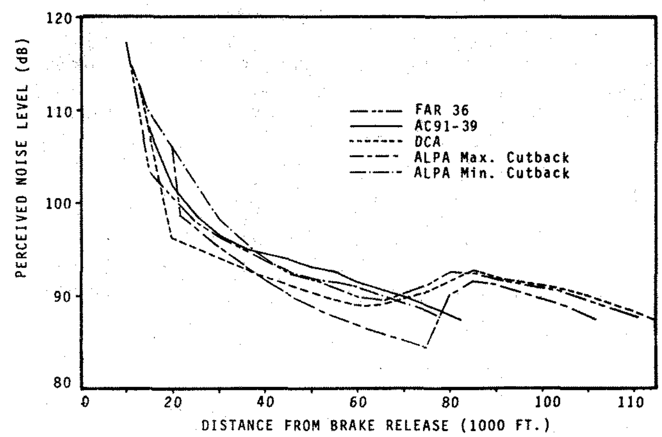

Fig. 9. Perceived Noise Levels Under Departure Path, B737-200 at 110,000 Pounds Take-Off Weight.

The noise levels for each aircraft weight configuration are shown in Figures 8 and 9, plotted against distance from brake release. In general, the two procedures (AC91-39 and ALPA Min. Cutback) calling for a smaller cutback in thrust (to maximum climb thrust) produce higher noise levels within about 10 miles of the brake release point than do the other departure schedules. At greater distances, these two procedures produce considerably less noise than the other three departure schedules, each of which calls for a larger thrust reduction. Figure 10 shows the fuel consumption for the two aircraft configurations used in this study for each of the departure schedules. The procedures AC91-39 and ALPA Min. Cutback (calling for small cutbacks in thrust) consume less fuel in reaching 10,000 feet altitude than the other schedules with larger thrust reductions.

To compare the effects of a thrust cutback before flap retraction with those of thrust reduction after cleanup, the noise levels of AC91-39, FAR 36 and DCA should be compared with the noise levels of the ALPA procedures. Figures 8 and 9 show that for both weights of the B737 used in this study, thrust cutback prior to flap retraction results in a reduction in noise level earlier in the flight profile than when thrust is reduced after flap retraction. In fact, an immediate drop in noise level upon cutback under the ALPA pro-cedures is only realized if the maximum cutback is utilized. By delaying thrust cutback until after flap retraction, the ALPA Min. Cutback schedule actually generates higher noise levels than the AC91-39 procedure (at the same cutback thrust) in the early portions of the flight profile, and is only marginally better at greater distances from the runway.

At these larger distances from the runway (more than 60,000 feet from brake release) the noise levels of the large cutback departure schedules begin to rise, with the exception of the ALPA Max. Cutback procedure. With this procedure, the delay in instituting thrust reduction until after flap retraction produces a sizeable advantage in terms of low noise level from 50,000 feet to 70,000 feet from brake release. Moreover, the eventual increase in noise level experienced under ALPA Max. Cutback is small enough to give it a continuing noise advantage over the other large cutback procedures.

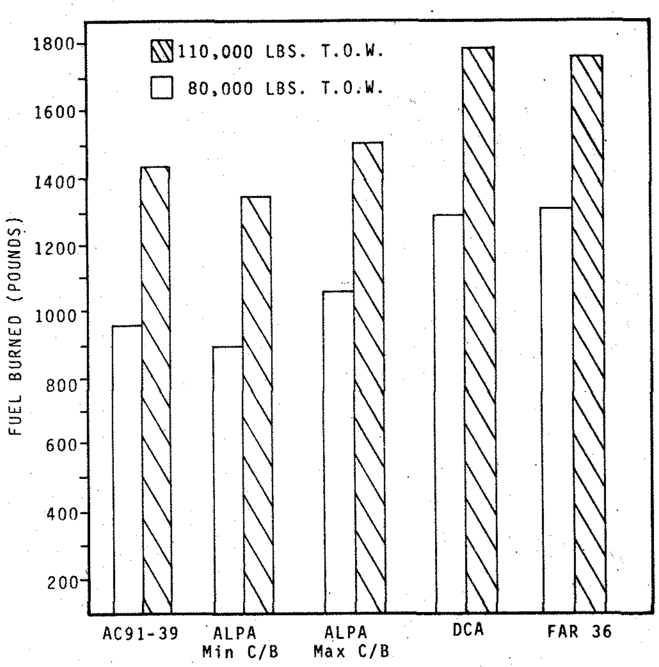

Fig. 10. Total Fuel Burned to 10,000 Feet Altitude, B737-200 at 80,000 and 110,000 Pounds Take-off Weight.

With respect to fuel consumption, the extent of thrust cutback is the more critical factor. As indicated previously, the two procedures calling for the least thrust reduction consume the least amount of fuel. However, in examining Figure 10, it is apparent that the large cutback in the ALPA Max. Cutback procedure does not penalize the aircraft too severely in terms of fuel consumption, in comparison with AC91-39 and ALPA Min. Cutback. It would seem that the small cutback procedures reduce total fuel consumption to 10,000 feet altitude by allowing the aircraft to reach that altitude quickly (or in short distances from brake release) even though their rate of fuel consumption is high. The larger cutback procedures, although burning fuel at lower rates, simply take too long to reach 10,000 feet altitude, thereby consuming larger quantities of fuel. The ALPA procedures tend to minimize the fuel penalty inherent in taking longer to reach 10,000 feet altitude because the aircraft climbs and accelerates in a clean configuration. This increases its climb rate and acceleration compared to the other procedures for the same cutback thrust level, while at the same time burning fuel at the rate dictated by the reduced thrust.

With the noise levels translated into Percent Words Correct to represent noise impact, the two quantities, noise impact and fuel consumption, are then combined in the Noise-Fuel Ratio (NFR). The logarithm of the NFR is plotted against distance from brake release in Figures 11 and 12. Figures 13 and 14 are enlargements of these plots in the regions closer to the runway.

Before discussing the curves in these Figures, some specific features should be explained. At very high noise levels, Williams' data (Reference 8) shows an extreme noise impact in terms of only a small percentage of words correctly understood. We have arbitrarily extrapolated the data of Reference 8 to a score of 5% words correct, and used that value as a cutoff for our noise impact. Thus, the curves in Figures 11 to 14 start at 5,000 feet from brake release (or 10,000 feet, depending on aircraft weight), where all profiles generate noise levels equal to or greater than those which correspond to the 5% words correct score. Because of the arbitrary cut-off at 5% words correct, the noise impacts of the profiles are the same, so the short horizontal lines at the beginning of each NFR curve reflect only the different fuel consumption for each departure procedure.

At large distances from brake release, the curves have been terminated at the point where the aircraft has reached 6,000 feet altitude. This was necessary because the noise data available to us did not provide values beyond 6,000 feet, so we would have had to extrapolate to greater altitudes. There was little point in doing so, because the noise levels were small enough at 6,000 feet to be equivalent to nearly 100% words correct in Williams' data, and therefore nominally zero impact. Beyond zero noise impact (100% words correct) the differences in the NFR curves would again reflect only the differences in overall fuel consumption.

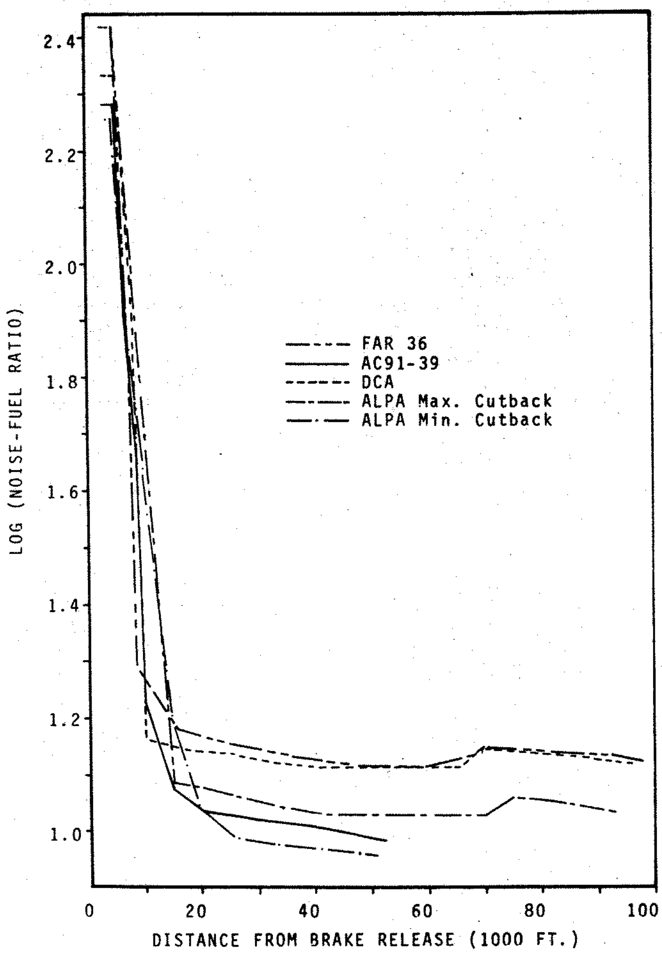

Fig. 11. Noise-Fuel Ratios for Departure Schedules, B737-200 at 80,000 Pounds Take-off Weight, Observer Indoors

Figures 11 and 12 illustrate the Noise-Fuel Ratios of the departure procedures at large distances. In those figures, it is seen that the arrangement order of the NFR curves is identical to the order between the departure schedules with respect to fuel consumption, for distances greater than 25,000 feet (35,000 feet for the heavier aircraft). Figures 8 and 9 show that there are differences in noise level for the

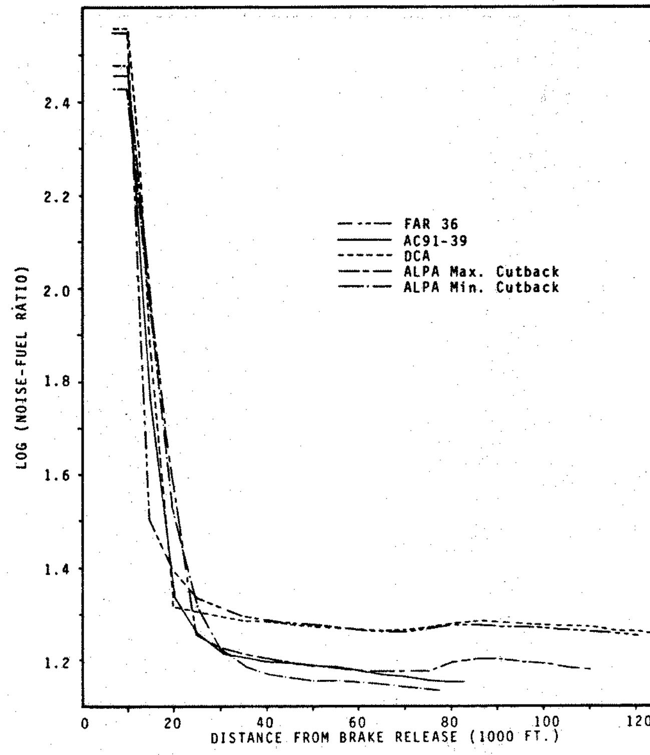

Fig. 12. Noise-Fuel Ratios Close to Airport, B737-200 at 110,000 Pounds Take-off Weight, Observer Indoors.

various departure procedures at these distances, so the NFR curves are reflecting the fact that such noise levels are not critical in terms of impact. For the range of noise levels experienced at these distances (less than 95 PNdB), Figure 3 shows that the speech interference is small (more than 90% words correct) and the varia-tion of impact with decreasing noise level is also small and practically linear. Even when the large cutback procedures call for a resumption of climb thrust levels, the resulting noise levels are such that the NFR curves rise slightly without changing their relative order. The region where noise impact and fuel consumption may provide some trade-off would therefore appear to be between the airport boundary (nominally 10,000 to 12,000 feet from brake release) and about 35,000 feet to 50,000 feet from brake release.

Figures 13 and 14 depict the NFR curves in this area, within some 6.5 and 9.5 miles from the airport boundary. There are differences in degree between the NFR curves for the 80,000 lb. airplane and those for the 110,000 lb.B737, but not of sufficient magnitude to require a separate discussion.

Generally, those procedures which utilize a large cutback in order to achieve low noise levels in the near region, namely DCA and ALPA Max. Cutback, lose the advantage of low noise to

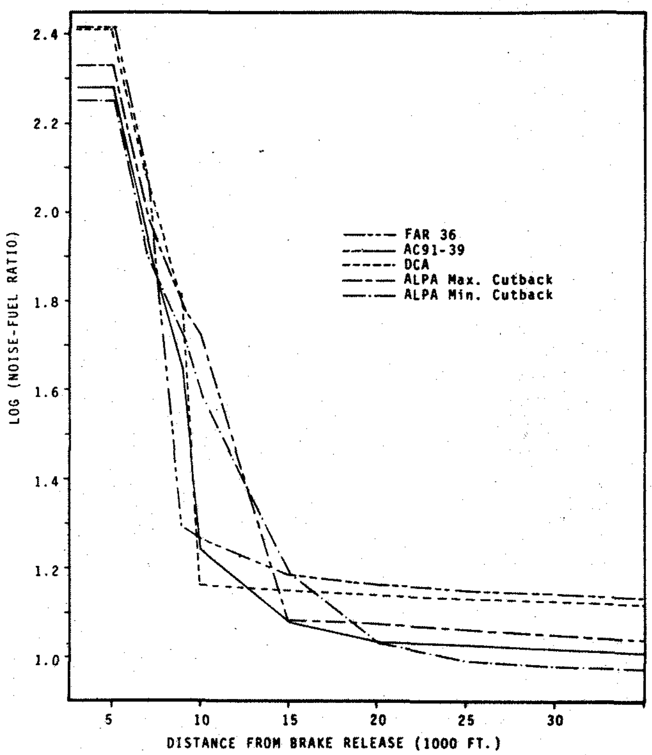

Fig. 13. Noise-Fuel Ratios Close to Airport, B737-200 at 80,000 Pounds Take-off Weight, Observer Indoors.

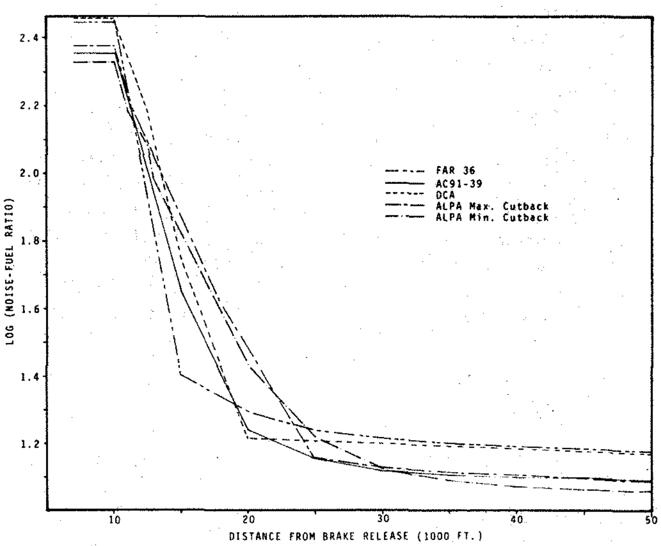

Fig. 14. Noise-Fuel Ratios Close to Airport, B737-200 at 110,000 Pounds Take-off Weight, Observer Indoors.

extra fuel consumption. With the exception of a short distance interval of less than 1/2 mile where the DCA procedure shows the lowest NFR value, both of these procedures are inferior (for the B737) to the AC91-39 schedule. The FAR 36 procedure also produces an NFR lower than the other procedures, but only at distances very close to the airport boundary. Indeed, for the light B737, the advantage of the FAR 36 procedure remains entirely within the nominal perimeter of the airport. Both ALPA procedures lose their effectiveness in the near region to higher noise levels because of the delay in reducing thrust to allow for flap retraction first. At larger distances from the airport, the ALPA Min. Cutback procedure realizes the lowest NFR values, due to both low noise in that region and low overall fuel consumption.

As a final section in the analysis, the Noise-Fuel Ratio for the heavier B737 was examined with the observer being impacted by the noise while out-of-doors. The results (Figure 15) are somewhat tentative due to a couple of assumptions that were made. The noise impact (% words correct versus PNL) found in Reference 8 (see Figure 2) was originally derived from listeners indoors, hearing aircraft noise as it would be perceived indoors. We have applied the same relationship to listeners impacted by aircraft noise while outdoors. Thus, we have assumed that the differential attenuation by frequency provided by residential-type construction does not materially affect the speech interference aspect of the noise, and that the recipient's ability to properly recognize words in the presence of a given level of noise is the same indoors and out. In view of the differen-

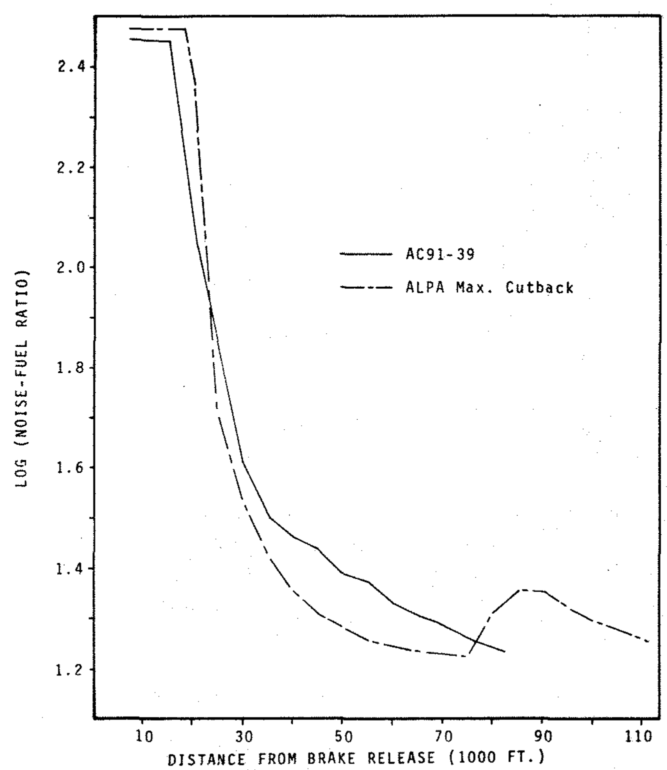

Fig. 15. Noise-Fuel Ratios for Two Departure Schedules, B737-200 at 110,000 Pounds Take-off Weight, Observer Outdoors.

ces in reaction to aircraft noise that are ascribed to location indoors versus outdoors [4,6], either or both of these assumptions may be inappropriate.

Figure 15 shows a change in the relative merits of procedures AC91-39 and ALPA Max. Cutback beyond 25,000 feet from brake release. For the outdoor impact situation, AC91-39 is still preferred up to 15,000 feet beyond the nominal airport boundary, then again for distances of more than 12 miles from that boundary. Within those two limits, ALPA Max. Cutback produces a lower Noise-Fuel Ratio. Figure 12 shows the NFR values in this region for indoor perception, where the AC91-39 and ALPA Max. Cutback are essentially equivalent. Where noise is high, as in this outdoor example, the NFR curves are more closely aligned with the relative ranking of the procedures based on noise level; where noise is low, the NFR curves reflect relative fuel consumption.

CONCLUSION

As stated previously, the method proposed in this paper is comparative, both with respect to the merits of departure schedules and with respect to impact at different points on the ground. Until such time as a common denominator value can be placed on both the noise impact and the fuel consumption (such as economic cost) it is not possible to assign a value to differences in NFR values, even to the extent of stating whether a given difference is significant or not. It is our hope that this present analysis and suggested index will encourage further analysis to both improve the index concept and provide the common denominator evaluation.

We have noted in the literature attempts to define a standard or preferred noise abatement departure profile. While our study is far from exhaustive, and we fully intend to examine other aircraft types in a similar manner, these present results suggest to us that a single standard or preferred noise abatement procedure may be difficult to define if both fuel economy and noise impact are to be considered. Depending upon the significance of a given difference in NFR, it may be necessary consider the location of noise to sensitive communities and the type and weight of departing aircraft before a suitable and effective noise abatement departure, which is justly economical of fuel, can be designated.

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APPENDIX A

This Appendix provides descriptions of departure schedules from Ref. 7, as they have been used in this study. All altitudes quoted are measured from the surface of the departure runway, nominally at the lift-off point.

I SMALL THRUST REDUCTION SCHEDULES

AC91-39 Departure Schedule

First Segment (roll and initial climb)

- Brake release; takeoff roll with take off thrust; rotate and climb to 35 ft. altitude and accelerate to V2 keas
- Retract gear, climb to 400 ft. altitude, accelerate to V2 + 10 keas
- Climb to 1500 ft. altitude, thrust = takeoff, speed = V2 + 10* keas, flaps = takeoff, and gear = retracted

Second Segment (thrust cutback)

- At 1500 ft. altitude maintain speed, reduce thrust to maximum climb thrust, perform partial flap retraction if speed permits
- Climb to 3000 ft. altitude with thrust = maximum climb, speed = V2 + 10* keas, flaps = takeoff or partial retraction if speed permits, and gear = retracted

Third Segment (normal climb)

- At 3000 ft. altitude maintain maximum climb thrust, retract flaps per flap retraction schedule, and accelerate to 250 keas with 500 to 1000 fpm rate of climb

* Indicates speed acceleration beyond V2 + 10 keas if pitch attitude is limited, or to enable a lesser flap setting during second segment, of if required for practical or safety reasons

- Climb and accelerate to 250 keas with thrust = maximum climb, speed = V2 + 10* to 250 keas, flaps = retracted, and gear = retracted
- When a speed of 250 keas and flap retraction are achieved, maintain maximum climb thrust and initiate normal climb schedule

ALPA Min. Cutback Departure Schedule

First Segment (roll and initial climb)

- Brake release; takeoff roll with takeoff thrust; rotate and climb to 35 ft. altitude, accelerate to V2 keas
- Retract gear, climb to 400 ft. altitude, accelerate to V2 + 10 keas
- Climb to 1000 ft. altitude with thrust = takeoff, speed = V2 + 10 keas (or greater if required), flaps = takeoff, gear = retracted

Second Segment (thrust cutback)

- At 1000 ft. altitude lower nose and accelerate to zero flap speed (VZF), retract flaps per schedule, maintain takeoff thrust and a pitch attitude within 1/2 initial value plus 0 to 3 deg. and a rate of climb not less than 500 fpm
- Climb and accelerate to VZF with thrust = takeoff, speed = V2 + 10 to VZF keas, flaps = retracted, and gear = retracted
- When a speed of VZF and flap retraction are achieved, reduce thrust to maximum climb thrust
- Climb to 4000 ft. altitude with thrust = maximum climb, speed = VZF keas, flaps = retracted, and gear = retracted

Third Segment (normal climb)

- At 4000 ft. altitude maintain maximum climb thrust and accelerate to 250 keas with 50 to 1000 fpm rate of climb
- Climb and accelerate to 250 keas with thrust = maximum climb, speed = VZF to 250 keas, flaps = retracted, gear = retracted
- When a speed of 250 keas is achieved, maintain maximum climb thrust and initiate normal climb schedule

II LARGE THRUST REDUCTION SCHEDULES

FAR 36 Departure Schedule

First Segment (roll and initial climb)

- Brake release; takeoff roll with takeoff thrust; rotate and climb to 35 ft. altitude; accelerate to V2 keas
- Retract gear; climb to 400 ft. altitude; accelerate to V2 + 10 keas
- Climb to 1000 ft. altitude with thrust = takeoff, speed = V2 + 10 keas (or greater if required), flaps = takeoff, gear = retracted

Second Segment (thrust cutback)

- At 1000 ft. altitude, maintain speed and reduce thrust to a setting which will give level flight with one engine inoperative or a 4 percent climb gradient, whichever thrust is greater. This setting will be referred to as cutback thrust.
- Climb to 3000 ft. altitude with thrust = cutback, speed = V2 + 10 keas, flaps = takeoff, gear = retracted

Third Segment (normal Climb)

- At 3000 ft. altitude maintain speed and gradually increase thrust to achieve maximum climb thrust at not less than 4000 ft.

thrust increasing from cutback to maximum climb, speed = V2 + 10 keas, flaps = takeoff, gear = retracted

- When maximum climb thrust is achieved, retract flaps per schedule and accelerate to 250 keas with 500 to 1000 fpm rate of climb
- Climb and accelerate to 250 keas with thrust = maximum climb, speed = V2 + 10 to 250 keas, flaps = retracted, gear = retracted
- When a speed of 250 keas and flap retraction are achieved, maintain maximum climb thrust and initiate normal climb schedule

ALPA Max. Cutback Departure Schedule

First Segment (roll and initial climb)

- Brake release; takeoff roll with takeoff thrust; rotate and climb to 35 ft. altitude; accelerate to V2 keas
- Retract gear, climb to 400 ft. altitude; accelerate to V2 + 10 keas
- Climb to 1000 ft. altitude with thrust = takeoff, speed = V2 + 10 keas (or greater if required), flaps = takeoff, gear = retracted

Second Segment (thrust cutback)

- At 1000 ft. altitude lower nose and accelerate to zero flaps speed (VZF), retract flaps per schedule, maintain takeoff a pitch attitude within 1/2 initial value plus 0 to 3 deg. and a rate of climb not less than 500 fpm
- Climb and accelerate to VZF with thrust = takeoff, speed = V2 + 10 to VZF keas, flaps = retracted, gear = retracted
- When a speed of VZF and flap retraction are achieved, reduce thrust to the greater setting for either a rate of climb of 1000 fpm or the following positive climb gradients if one engine should become inoperative: two-engine aircraft = 1.2 percent, three-engine aircraft = 1.5 percent, four-engine aircraft = 1.7 percent. This setting will be referred to as cutback thrust.
- Climb to 4000 ft. altitude with thrust = cutback, speed = VZF keas, flaps = retracted, gear = retracted

Third Segment (normal climb)

- At 4000 ft. altitude, gradually increase thrust to maximum climb thrust, accelerate to 250 keas with 500 to 1000 fpm rate of climb
- Climb and accelerate to 250 keas with thrust increasing from cutback to maximum climb, speed = VZF to 250 keas, flaps = retracted, gear = retracted
- When a speed of 250 keas and maximum climb thrust are achieved, initiate normal climb schedule
- When a speed of 250 keas and flap retraction are achieved, maintain maximum climb thrust and initiate normal climb schedule

DCA Departure Schedule

First Segment (roll and initial climb

- Brake release; takeoff roll with takeoff thrust; rotate and climb to 35 ft.; accelerate to V2 keas
- Retract gear, climb to 400 ft. altitude, accelerate to V2 + 10 keas
- Climb to 1500 ft. altitude with thrust = takeoff, speed = V2 + 10 keas (or greater if required), flaps = takeoff, gear = retracted

Second Segment (thrust cutback)

- At 1500 ft. altitude maintain speed and reduce thrust to a cutback thrust computed for hot day conditions at maximum gross takeoff weight to give approximately 500 fpm rate of climb
- Continue to climb until ten nautical miles distant from brake release point

Third Segment (normal climb)

- At ten nautical miles distance from brake release maintain speed and gradually increase thrust to achieve maximum climb thrust at not less than 4000 ft. altitude
- Climb to the altitude required to achieve maximum climb thrust with thrust increasing from cutback to maximum climb, speed = V2 + 10, flaps = takeoff, and gear = retracted
- When maximum climb thrust is achieved, retract flaps per schedule and accelerate to 250 keas with 500 to 1000 fpm rate of climb
- Climb and accelerate to 250 keas with thrust = maximum climb, speed = V2 + 10 to 250 keas, flaps = retracted, gear = retracted